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LEAK-RATE TESTING OF THE NASA PLUM BROOK

REACTOR CONTAINMENT VESSEL

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34

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SUMMARY

The leak rate of the 520,000-cubic-foot Plum Brook Reactor containment vessel has been measured by two methods, the absolute-temperature-pressure method and the reference-system method. Both methods are described, and the equations for leakage in each method are investigated in detail. It is analytically determined that thermal-time-lag effects in small diameter reference systems are negligible.

The results of three tests in which both methods were employed simultaneously are presented. A distinctive feature of one of the tests was the verification of the accuracy of results by using a known leak rate. Various test experiences are also presented. Some of the more significant results and conclusions are: (1) The accuracy with which a reference system senses the average vessel air temperature is likely to be limited by sampling errors rather than by thermal-time-lag errors, if it is of proper design. (2) The thermal-time-lag effects in the reference systems employed here were negligible, and hence both systems were temperature compensating. (3) In all tests the reference-system results showed less scatter than the absolute-method results. (4) In all tests the results of both methods were in substantial agreement. (5) The absolute method offered greater overall simplicity than the reference-system method, although the latter proved to be an accurate and satisfactory method of measurement. (6) The pressure-differential data from the reference-system method permitted the convenient approximation of the leak rate, which was valuable in reducing the overall testing time. (7) The accuracy of leak-rate results can be determined conveniently by superimposing a known leak rate upon the vessel leak rate during part of the test period.

INTRODUCTION

The NASA Plum Brook Reactor (PBR) (fig. 1) is situated 3 miles south of the city of Sandusky, Ohio, and about 4 miles from the center of population. The facility is described in detail in an unpublished NASA report, the "Final Hazards Summary, Plum Brook Reactor Facility," by A. B. Davis, B. Lubarsky, and T. M. Hallman, December 1959 (vols. 1 to 3). Because of the density of the surrounding population, extreme efforts have been made to safeguard against an accidental release of fission products to the surrounding environs. One of the structural deterrents to such a release is a virtually leakproof containment vessel that completely surrounds the reactor core and the pressure tank (fig. 2). How leakproof the vessel must be is expressed in terms of a maximum allowable leak rate, which is established from considerations of

(1) The maximum credible nuclear accident and the resultant fission product concentration in the air of the containment vessel

(2) Meteorology as related to the dispersion of fission products

(3) Permissible radiation exposure to the general public

For the PBR containment vessel an allowable leak rate of 115 standard cubic feet per day at an overpressure of 0.3 pound per square inch gage has been established. Detailed considerations leading to the establishment of these limiting requirements are presented in the "Final Hazards Summary" (vols. 1 and 2).

In order to ensure that the foregoing requirements are met, periodic leak-rate measurements must be conducted. Since the volume of the PBR containment vessel is roughly 500,000 cubic feet, it becomes apparent that the accurate measurement of a leak rate of the order of 100 cubic feet per day is likely to be a formidable and time-consuming problem, even under ideal conditions of constant temperature, volume, water-vapor pressure, etc. The attainment of ideal conditions, however, is a practical impossibility.

As an example of the difficulties involved in this measurement, consider the average vessel air temperature. The importance of temperature measurements may be realized by noting that a change in the average vessel air temperature of only 1° F will produce a pressure change of 0.8 inch of water, while the leakage of 100 cubic feet of air will also produce a pressure change of 0.8 inch of water. Thus, a 1° error in the average temperature measurement could completely mask the presence of a leak of the order of the maximum allowable. In addition, obtaining accurate and precise local temperature measurements does not ensure an accurate average air temperature measurement; this is true because of the concurrence of (1) spatial thermal variations, which are unavoidable in vessels of such large volume, and (2) diurnal temperature variations, which cause fluctuations in the average vessel air temperature with time.

Numerous other factors may further increase the difficulty of a leak-rate measurement. Thus, it is not unusual that testing periods of the order of a week have been required at some reactor sites to determine the leak rate with sufficient accuracy. The need for an accurate testing method requiring a short period of time is acutely apparent for reasons of economy alone. The two testing methods most commonly employed have been the absolute-temperature-pressure method and the reference-system method. Both have had varying degrees of success.

In the absolute-temperature-pressure method a number of temperature-sensing elements are judiciously placed within the pressurized containment vessel to measure the spatial air temperature distribution, from which an average temperature is determined. An absolute-pressure measurement is also taken, which makes it possible to calculate the volume of air at standard conditions within the vessel. The air volume is plotted as a function of time, and the slope of the resulting straight line is the leak rate. Past experiences indicate, however, that it may be a matter of days before a definite trend is discernible because of the large scatter of data. Indeed, the principal shortcoming of the absolute method is the fact that the accuracy to which the combination of absolute pressure and temperature measurements may be made without being impractical is such that it yields excessive scatter in the plotted leakage results. To counteract this difficulty, it is necessary either to extend the test period or in some way increase the accuracy of the measurements.

Periodic tests of the Experimental Boiling Water Reactor (EBWR) vessel at the Argonne National Laboratory have been conducted in which the absolute method was employed (ref. 1). In the initial test a period of 8 days was required before the leak-rate determination was deemed satisfactory (ref. 2). In this initial test the pressure measurements were read to 0.01 inch of mercury and temperature conversions were to 0.1° F. For subsequent tests an absolute manometer was designed and built that could be read to 0.001 inch of mercury and "a method for calculating, direct from millivolt values was devised to eliminate the inaccuracies introduced by conversion to $^\circ$F." By these means the length of the test period was reduced to 1 or 2 days.

The second method of measurement, the reference-system method, was first proposed in reference 3 and used to test the Vallecitos Boiling Water Reactor (VBWR) vessel of the General Electric Company. Essentially this method consists of measuring the pressure differential between the vessel being tested and a leakproof system of tubing placed within the vessel, both being at the same overpressure initially. If both the reference system and the containment vessel remain at the same temperature, the pressure differential is directly proportional to the weight loss of air. Hence, the principal attraction of this method is its temperature compensation (disputed by some), which eliminates all need for making the direct temperature measurements required in the absolute method and supposedly results in an increase in the accuracy of the results. In the reference-system method it is, of course, necessary that the system be placed in such a position that it is at the same average temperature as the vessel air. Even though the foregoing has been accomplished, however, an objection may be raised that during one diurnal temperature cycle there will be only two times when the reference system and vessel temperature are the same. This is true because the tube wall in itself offers a resistance to the passage of heat, and, therefore, the temperature of the air within the tube must necessarily lag behind the vessel air temperature.

Because of such possible practical difficulties, the objection is sometimes raised that the reference system is not temperature compensating and, hence, in the last analysis requires both temperature and pressure measurements of the same type and accuracy as required in the absolute method. Yet, in view of these apparently serious objections, the successful use of the reference-system method is reported in references 3 and 4. The most striking success was obtained when the Dresden containment sphere was tested for a 30-hour period (ref. 4). It is stated that the absolute method would have required a testing period of 1 week in order to have been of comparable accuracy. In tests of a volume of much smaller magnitude (14,500 cu ft) at the Lewis Research Center zero-power research reactor both methods were employed. The two methods yielded closely agreeing results, but the data from the reference system were more consistent and convenient (unpublished NASA test data).

In contrast to the foregoing experiences, however, tests of the Dido and Merlin containment vessels (at the atomic research installation of the Landes Nordheim-Wesfalen at Julich, Germany) by both methods indicated the absolute method to be superior (ref. 5). In fact, the measurements taken by the reference-system method could not be evaluated because the reference system did not show sufficient tightness.

The conflicting experiences reported make the choice of a leak-rate testing method somewhat problematical. Probably the best introduction to the problems involved in various testing methods may be found in reference 2. Also, a brief survey of testing methods may be found in reference 6.

In the first three PBR tests the reference-system method was employed. In addition, however, the measurements of the vessel air temperature, which were made in these tests primarily for general monitoring purposes, were also used to determine the leak rate by the absolute method. Thus, the results of both methods have been compared in order to aid test engineers in the choice of a testing method. In addition, certain analytical investigations were made with the purpose of establishing the validity of some of the objections to the reference-system method.

The purposes of this paper are

(1) To describe, analyze, and compare the methods used to measure the PBR containment vessel leak rate

(2) To present some of the experiences encountered in testing the PBR containment-vessel

(3) To describe some of the design features of the PBR containment vessel that ensure adequate containments

It should be added that the major part of this report is devoted to the reference-system method of measurement in order to clarify both its strong and weak points. The same treatment was not believed necessary for the absolute method, since the measuring methods and instruments involved are quite familiar and straightforward.

ANALYTICAL PHASE

Discussion of Equations Employed

In order to clarify the differences between the reference-system and absolute methods, it is helpful to examine the analytical expression for leakage in each method.

At the initiation of the test by the absolute method, the weight of air within the pressurized vessel is

$$W_{v,1} = \frac{P_{v,1}V_{v,1}}{RT_{v,1}} \tag{1}$$

from the equation of state for a perfect gas. (All symbols are defined in appendix A.) At any later time, the weight of air is

$$W_{v,2} = \frac{P_{v,2}V_{v,2}}{RT_{v,1}} \tag{2}$$

If a constant vessel volume is assumed, the fractional loss of contained air from equations (1) and (2) is

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}}\frac{T_{v,1}}{T_{v,2}} \tag{3}$$

Modifications of equation (3) necessitated by factors such as a changing vessel volume and varying water-vapor content of the air are considered elsewhere in this report.

In an actual test a system of temperature sensors is required to measure $T_{v,1}$ and $T_{v,2}$. Generally the measured average temperature will not be identical to the true average temperature because of instrument inaccuracies, human error, and inadequate sampling. Thus, the leakage is computed from a modified form of equation (3)

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2}}{P_{v,1}}\frac{T_{s,1}}{T_{s,2}} \tag{4}$$

The true fractional weight loss may be obtained from equation (4) by multiplying both $T_{s,1}$ and $T_{s,2}$ by appropriate temperature ratios in the following manner:

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}}\frac{T_{s,1}}{T_{s,2}}\frac{T_{v,1}}{T_{s,1}}\frac{T_{s,2}}{T_{v,2}} \tag{5}$$

which is identical to equation (3). The preceding operation is performed only for a later comparison of the absolute and reference-system methods.

In the reference-system method the vessel and reference system are first brought to the testing pressure. The reference system is then closed at time τ_0, and the required periodic measurements are begun. Since a period of time has elapsed between closing the reference system and taking the first set of readings, the difference in pressure between the reference system and the containment vessel is

$$P_{r,1} - P_{v,1} = \frac{W_{r,1}R_{r,1}T_{r,1}}{V_{r,1}} - \frac{W_{v,1}R_{v,1}T_{v,1}}{V_{v,1}} = \Delta P_1 \tag{6}$$

At any later time,

$$P_{r,2} - P_{v,2} = \frac{W_{r,2}R_{r,2}T_{r,2}}{V_{r,2}} - \frac{W_{v,2}R_{v,2}T_{v,2}}{V_{v,2}} = \Delta P_2 \tag{7}$$

It is assumed that

(1) The value of R is constant throughout the test, and is the same in both the reference system and the containment vessel.

(2) The density of air within the reference system is constant.

(3) The reference-system and the containment-vessel volumes are constant.

Then the weight of air in the vessel at both times is

$$W_{v,1} = \frac{V_v}{T_{v,1}}\left(\frac{W_r}{V_r} T_{r,1} - \frac{\Delta P_1}{R}\right) \tag{8}$$

$$W_{v,2} = \frac{V_v}{T_{v,2}}\left(\frac{W_r}{V_r} T_{r,2} - \frac{\Delta P_2}{R}\right) \tag{9}$$

From equations (8) and (9) it can be determined that

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{W_r V_v}{V_r W_{v,1}}\left(\frac{T_{r,1}}{T_{v,1}} - \frac{T_{r,2}}{T_{v,2}}\right) + \frac{V_v}{RW_{v,1}}\left(\frac{\Delta P_2}{T_{v,2}} - \frac{\Delta P_2}{T_{v,1}}\right) \tag{10}$$

Using the equation of state to modify equation (10) produces the final expression for the percent loss according to reference 2

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{P_{r,1}}{P_{v,1}} \frac{T_{v,1}}{T_{r,1}}\left(\frac{T_{r,1}}{T_{v,2}} - \frac{T_{r,2}}{T_{v,2}}\right) + \frac{1}{P_{v,1}}\left(\frac{T_{v,1}}{T_{v,2}} \Delta P_2 - \Delta P_1\right) \tag{11}$$

Equation (11) suggests that, even though the reference-system temperature is equal to the vessel air temperature at all times (i.e., $T_{r,1} = T_{v,1}$ and $T_{r,2} = T_{v,2}$), it is still necessary to measure the vessel air temperature continuously. If the vessel air temperature measurement is required, it is pointless to use the reference-system method, which supposedly offers the advantage of eliminating direct temperature measurements. It is shown subsequently, however, that direct temperature measurements are not required.

Without any additional assumptions, equation (11) may be rearranged into the more meaningful and convenient form

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}}\left(\frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2}\right)\frac{T_{v,1}}{T_{r,1}}\,\frac{T_{r,2}}{T_{v,2}} \tag{12}$$

From equation (12) it would still seem that temperature measurements must be made; however, if the reference-system temperature could be made very nearly equal to the containment vessel temperature, both temperature ratios in equation (12) would be close to unity. Then the fractional weight loss could be determined accurately by pressure measurements alone. In practice this might be accomplished (1) by minimizing the thermal time lag of the reference system by judicious design and (2) by distributing the system in such a way that the vessel volume is adequately sampled. The temperature ratios of equation (12) could then be neglected, and equation (12) would become

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2}}{P_{v,1}}\left(\frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2}\right) \tag{13}$$

The scatter in the fractional loss indications calculated from equation (13) would, thus, indicate how close to unity the neglected temperature ratios actually were. Lest neglecting these temperature ratios be viewed as a shortcoming of the reference-system method, it should be noted that two temperature ratios must likewise be neglected in the absolute method (see eqs. (5) and (4), which are the counterparts to eqs. (12) and (13), respectively). Actually, all sampling measurements involve neglecting such ratios. When the indicated and actual quantities are identical, these ratios will equal unity and there will be no scatter in the results. The indicated and actual quantities are not always identical, however, and the scatter of data is merely accepted.

It should be noted that the reference system is nothing more than a large gas thermometer that offers the advantage of continuous spatial sampling compared to the point sampling in the absolute method. On the other hand, a reference system may conceivably have a significant thermal time lag, while the thermocouples used in the absolute method will respond instantly to local temperature changes. In the following section the magnitude and consequences of thermal-time-lag effects in the reference-system method are investigated.

Thermal Time Lag in Reference System

In the limited literature available, it is pointed out that during temperature transients a reference system is in error because of an unavoidable thermal time lag; however, the magnitude of this error has not been clarified.

This problem is solved here by first making the simplifying and conservative assumption that the reference-system wall is replaced by air. Thus, the reference system is viewed as an infinitely long solid cylinder of air in which heat transfer occurs only by conduction and whose surface undergoes a daily sinusoidal temperature variation $T \sin \omega\tau$. The temperature at any point within the cylinder is given in reference 7 as

$$t = T \frac{M_0(\omega' r)}{M_0(\omega' a)} \sin\left[\omega\tau + \theta_0(\omega' r) - \theta_0(\omega' a)\right] \tag{14}$$

where $M_0(z)$ and $\theta_0(z)$ are Bessel functions and are tabulated for various values in reference 8.

From equation (14) both the amplitude and phase angle of the temperature at the cylinder centerline are seen to be functions of a, ω, and $1/\kappa$. Since $M_0(z)$ and $\theta_0(z)$ are functions that increase with an increasing z, it is apparent that the difference between the reference-system and containment-vessel air temperatures may be minimized by making the tube diameter as small as practicable.

For bare-shell testing the amplitude of the daily temperature variation may be about 15° F. For final periodic testing the temperature range is usually somewhat reduced because of insulating construction features and perhaps an air-conditioning system. The most severe cycle encountered in PBR tests had an amplitude of 8° F and a period of 8 hours. The centerline temperatures of 12- and 24-inch-diameter cylinders are shown for both cases in figure 3.

There is virtually no damping of the temperature wave in either system; however, the temperature differences arising from the phase shifting are quite significant, 2.2° and 0.7° F for the 24- and 12-inch systems, respectively. For a 2-inch-diameter system, such as that employed in PBR tests, the largest temperature difference occurring for the same temperature variations is calculated to be less than 0.01° F.

Indicated and actual percent loss values for the three reference systems calculated from equation (12) are listed in table I for the following conditions:

Initial and final containment-vessel temperatures, $T_{v,1} = T_{v,2}$, °R 530.00
Initial containment-vessel pressure, $P_{v,1}$, in. water 510.0
Final containment-vessel pressure, $P_{v,2}$, in. water 508.5
Initial actual pressure change, ΔP_1, in. water 0
Final actual pressure change, ΔP_2, in. water 1.5

The actual percent loss is obtained from equation (12) where both temperature ratios are unity. The indicated percent loss values are obtained by inverting both temperature ratios in equation (12). The percent error calculated for each system is the maximum percent error expected and is therefore quite conservative.

The error in the 2-inch system is seen to be quite acceptable. From a practical standpoint, it would be much more convenient to employ a system smaller than 2 inches in diameter. The smallest size employed would be limited by condensation effects; that is, the system should be sufficiently large to allow condensate to form within the system without forming slugs obstructing pressure propagation to the manometer. It is believed that a 1/2-inch-diameter tube could easily be employed under any conditions without difficulties of this type. With such a system the error arising from thermal-time-lag effects may be considered negligible. Accordingly, it may be concluded that the accuracy with which a reference system senses the average vessel air temperature is likely to be limited by sampling errors rather than by errors due to a thermal time lag.

Accuracy and Precision of Measurements

A leak-rate test is made difficult principally because numerous factors, which in many tests would be considered insignificant second-order effects, may vitally affect the accuracy and meaningfulness of the results if neglected. For example, the necessity of measuring a representative average vessel air temperature with great accuracy and precision is clearly evident from table I. This measurement is made difficult principally because a temperature field must be measured. Thus, in order to obtain an accurate indication of the average air temperature, it is necessary to employ a number of temperature sensors, each of which is a representative sample of part of the vessel volume. When the spatial thermal gradients are not severe, the average temperature will be indicated accurately by the arithmetic mean temperature. With increasingly severe gradients, however, the arithmetic mean temperature represents the average temperature with decreasing accuracy. Thus, two questions are suggested: (1) what is the adequate number and location of sensing elements, and (2) how may spatial thermal gradients be minimized.

The latter problem may be solved by mixing and circulating the vessel air by means of a system of fans. This solution, however, does introduce the possibility of yielding erroneous results if fast-response temperature sensors, such as thermocouples, are used. A fast-response instrument would react to virtually every passing air current. At the time when measurements are taken, a true but nonrepresentative temperature could thus be indicated because of the passage of an unusually warm or cold air mass. Perhaps if the thermocouples were embedded in small copper blocks, spurious temperature fluctuations would be damped.

The answers to the former question are more nebulous. Certainly much depends on the specific physical characteristics of the vessel being tested. In any case, the effectiveness of a measuring system will be reflected in the scatter of the percent loss determinations. This is true because, in any experiment whose results are obtained from the measurement of a number of variables, the inaccuracies of a particular variable will be propagated into the results. The uncertainty in a result due to the uncertainties in the measured variables may be estimated from the "second-power equation"

$$\epsilon_{\Re} = \sqrt{\left(\frac{\partial \Re}{\partial v_1}\,\epsilon_1\right)^2 + \left(\frac{\partial \Re}{\partial v_2}\,\epsilon_2\right)^2 + \ . \ . \ . + \left(\frac{\partial \Re}{\partial v_n}\,\epsilon_n\right)^2} \tag{15}$$

where $\epsilon_{\Re}$ is the uncertainty interval of the result; $\Re$ is the result and is a linear function of n independent variables, each of which is normally distributed; and ϵ_i is the uncertainty interval for the variables (refs. 9 and 10).

(When eq. (15) is used, it is necessary to assign an estimated uncertainty interval to each measurement, together with the odds that the true value will be found within this interval if the measurement were repeated a large number of times.) Thus, in a leak-rate test the combination of a consistent trend of data and little scatter is a good indication that the average temperature and other relevant independent variables have been measured with sufficient accuracy. The comparative effects of temperature and pressure measurement errors in the absolute and reference system methods are discussed in appendix B.

It is quite useful to note that since a leak rate is measured in these tests fixed errors are of secondary importance. Thus, in measuring temperature, it may simply be assumed that the thermocouples employed follow the standard temperature-emf relation, even though the characteristics of a particular thermocouple will undoubtedly differ slightly from the standard. Over the small temperature range encountered (30° F), however, the temperature-emf relation for any thermocouple is for all practical purposes linear. Thus, if standard thermocouple temperature tables are used, the actual and the table values will differ but by a constant amount. This difference shifts the level of the leak rate but leaves its magnitude virtually unchanged. Hence, the precision of measurement assumes a more important role since fixed calibration errors do not seriously affect the accuracy of a leak-rate measurement. The largest errors would most likely be caused by inadequate and nonrepresentative sampling of the 500,000-cubic-foot volume. These errors would be of a random nature, unlike the fixed calibration errors just discussed.

Proper sampling is of such great importance that it is conceivable that, because of the typically large containment-vessel volume, a measuring system could measure properties not representative of average conditions, and the indicated leak rate would be merely a reflection of localized conditions. Therefore, it is desirable to have some positive means of illustrating the accuracy of results. A measuring method is not available to serve as a standard of comparison; otherwise, it would be unnecessary to employ any other methods. Hence, some indirect means must be used to verify the accuracy of results; in PBR tests this was accomplished by using a known leak rate. In this method a known leak rate is superimposed upon the existing vessel leak rate during the latter part of the test. This produces a corresponding change of slope in the curve of indicated fractional weight loss as a function of time if the measuring system is an accurate one.

In the tests described in the following sections the reference-system and absolute methods were used simultaneously. The spatial orientation of both measuring systems was essentially the same. Hence, to an extent the comparative accuracy and precision of the two methods should be graphically indicated by the plotted percent loss results.

EXPERIMENTAL PHASE

Description of Containment Vessel

The reactor core and its pressure tank are housed within a cylindrical steel tank (containment vessel) having an elliptical top, as shown in figure 2. It is designed to contain the products of the maximum credible accident. The containment vessel has an inner diameter of 100 feet, and its height above grade is approximately 53 feet. The wall extends downward to the shielding-pool floor level, 25 feet below grade, and then continues on as the containment vessel bottom. The shielding pool, which surrounds the reactor pressure tank, is approximately 70 feet in diameter and is divided into quadrants (figs. 2 and 4). Surrounding the pool and inside the containment tank is an annular space 13 feet wide and 25 feet deep. Part of the annulus is occupied by a canal. The canal and three of the quadrants are normally filled with water to a depth of 25 feet; the exposed water surface area is 3860 square feet.

The containment vessel is surrounded by the reactor building to a height of 27 feet above grade. The dome is covered with 2 inches of fiber glass insulation. The wall and dome structure are 3/4-inch plate, while the bottom disk is welded 3/8-inch plate.

Penetrations of the vessel fall into three categories: welded, potted, and gasketed. Service lines are welded, electrical lines are potted, and all doors are gasketed. Since potted and gasketed seals are most susceptible to leakage, these two types are employed in a double-seal arrangement (fig. 5) with the volume between being maintained under a vacuum. The potting compound that has been most satisfactory to date is Minnesota Mining and Manufacturing type EC 801. The vacuum system returns any collected leakage to the containment vessel.

The containment vessel is maintained at 1 inch of water below atmospheric pressure during normal operation. Access to the vessel is gained through two sets of air-lock doors. Air pressure between the doors is maintained between atmospheric and the containment vessel pressure. Thus, under normal operating conditions, any leakage would be into the vessel.

Apparatus

The reference system employed in each of the first three tests conducted consisted of a 20-foot length of 2-inch-diameter copper tubing, which was connected to an inclined manometer located immediately outside the vessel by means of an 80-foot length of 1/4-inch copper tubing (fig. 6). The 2-inch tube was located at the vessel centerline.

An additional reference system was employed in the first test only. It consisted of a 60-foot length of 1-inch-diameter copper tubing, which was connected to a micromanometer by means of a 20-foot length of 1/4-inch copper tubing. The 1-inch tube was placed diagonally within the vessel as shown in figure 6.

The remainder of the apparatus employed is as follows:

(1) One 10-inch inclined water manometer for measuring the pressure differential between the containment vessel and the 2-inch-diameter reference system; least division, 0.01 inch

(2) One 25-inch micromanometer for measuring the pressure differential between the containment vessel and the 1-inch-diameter reference system; least division, 0.001 inch

(3) One 10-foot water manometer for measuring the pressure differential between the containment vessel and the atmosphere; least division, 0.1 inch

(4) One standard precision mercury barometer; least division, 0.01 inch

(5) One gas flowmeter for metering a controlled leak; range, 0 to 165 cubic feet per day; least division, 0.1 cubic foot

(6) Two Foxboro humidity detectors (Dewcels) for measuring the partial pressure of water vapor in the vessel atmosphere; least count, 0.1° F dew-point temperature

(7) One potentiometer for humidity-detector and thermocouple measurements; least division, 0.001 millivolt

Both the micromanometer and inclined manometer were filled with a fluid that had a saturated vapor pressure of 0.00005 inch of water at 77° F to eliminate the necessity of making vapor-pressure corrections in the reference system.

The direct temperature measurements required by the absolute method were obtained by means of

(1) A single platinum resistance thermometer located at the vessel center

(2) Three iron-constantan thermocouples soldered to the outer surface of the 2-inch-diameter reference-system tube

(3) One Mueller bridge for the resistance thermometer measurements; least division, 0.0001 Ω

Test Procedure

All tests were accelerated; that is, the vessel was tested at an overpressure of 4 pounds per square inch rather than the 0.3-pound-per-square-inch overpressure expected in the event of the maximum credible accident. The allowable leak rate at 4 pounds per square inch gage is 1530 standard cubic feet per day.

All instrumentation was tested and checked out prior to leak-rate testing. The entire reference system was checked for leaks in two stages: (1) the reference system (fig. 7) was pressurized with helium, and all joints and valves were tested with a helium mass spectrometer; (2) with no fluid in the inclined manometer and the 10-foot manometer filled, the system was pressurized with helium to 4 pounds per square inch gage from the vessel side of valve 2. A helium mass spectrometer was again used to search for leaks. With the system still at 4 pounds per square inch gage, the 10-foot water manometer was used to indicate the pressure changes of the reference system over a 48-hour period. During this period, the system was also monitored for changes in temperature and barometric pressure. If no leaks were discovered, the system was depressurized and installed within the containment vessel for use in the leak-rate test.

After all necessary instrumentation was installed inside the vessel, the four air-conditioning units (fig. 2) were activated. Throughout the test the vessel air was circulated by these units, which are spaced equally along the vessel wall. Each unit circulates air upward along the wall and across the dome toward the center of the vessel, where mixing occurs.

The vessel was isolated, as in the event of the maximum credible accident, and pressurized to 1 pound per square inch gage. The containment vessel was then given an audiovisual check for large leaks. After any leaks found in this check were eliminated, the vessel was further pressurized to 4 pounds per square inch gage. During pressurization, valves 2, 3, 5, and 6 of the reference system (fig. 7) were opened, so that the reference system and the containment vessel were pressurized simultaneously. After valves 2 and 3 were closed, isolating the reference system from the containment vessel, a thorough soap-bubble check was made of all likely points of leakage (electrical penetrations, doors, etc.). Throughout the soap-bubble check the differential pressure between the containment vessel and the reference system was monitored. As soon as the pressure-time data appeared to indicate a leak rate significantly lower than that allowable, the recording of the data was begun.

Data were taken at 1-hour intervals for a period of 60 hours and included the following: resistance-thermometer temperature, barometric pressure, containment-vessel gage pressure, differential pressure between the containment vessel and the reference system(s), thermocouple temperatures at three points along the 20-foot reference system, and the dewpoint at two points along the vessel centerline. The approximate locations of the various instruments are shown in figure 6.

Normally, the first 48 sets of data points are used to determine the vessel leak rate. During the next 12 hours, valves 1 and 4 are opened and adjusted to permit air to be bled from the vessel through a gas flowmeter at a rate roughly equal to the allowable.

Correction Factors and Calculations

Correction factors. - Usually leak-rate test data need a number of correction factors. Possible sources of difficulty are

(1) Change in containment-vessel volume caused by

   (a) Thermal expansion

   (b) Pressurization of vessel

   (c) Change in level of shielding-pool water caused by evaporation or leaks

(2) Change in reference-system volume caused by

   (a) Thermal expansion

(b) Change in level of fluid in attached manometer

(3) Change in water-vapor pressure in containment-vessel air

(4) Change in water-vapor pressure in reference-system air

(5) Absorption of containment-vessel air by shielding-pool water

(6) Thermal radiation from containment-vessel walls to temperature sensors

For PBR tests where mild temperature fluctuations were expected, correction factors were employed for changes in the containment-vessel volume caused by changes in the level of the shielding pool water, changes in the reference-system volume caused by changes in the fluid level in the attached manometer, and changes in the water-vapor pressure in the containment-vessel air. In order to correct for changes in water-vapor pressure, equations (4) and (13) are written

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2} - (P_{h,2} - P_{h,1})}{P_{v,1}} \frac{T_{s,1}}{T_{s,2}} \tag{16}$$

and

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2} - (P_{h,2} - P_{h,1})}{P_{v,1}} \frac{P_{v,1} + \Delta P_1}{P_{v,2} + \Delta P_2} \tag{17}$$

The correction for changes in the reference-system volume compensates for the lower indicated percent loss which would result from a decrease in the reference-system pressure. For the 20-foot system it was calculated that a change of 1 vertical inch in the liquid level in the inclined manometer would produce a change in reference-system pressure of 0.092 inch of water.

Calculations. - The following is a set of typical test data:

$T_{s,1}$, $^{\circ}R$	528.96	$T_{s,2}$, $^{\circ}R$	531.15
$P_{v,1}$, in. water	509.75	$P_{v,2}$, in. water	508.15
ΔP_1, in. water	2.07	ΔP_2, in. water	5.81
$P_{h,1}$, in. water	6.44	$P_{h,2}$, in. water	7.22

From these values and equations (16) and (17), the percent loss is calculated to be 0.881 and 0.950 percent for the absolute and reference-system methods, respectively. These results should be considered as being in good agreement. It should also be noted that agreement of the individual percent loss determinations is not as important as the agreement of the trends of the determinations since the leak rate is of primary concern.

In these tests, the best fit straight line through each set of percent loss results was obtained by the method of least squares. To provide some rational basis for determining the confidence interval of the least-squares leak rate, the percent loss results were assumed to have a gaussian distribution. The standard deviation was then calculated by standard statistical methods.

Results

Test 1. - The results of the first PBR leak-rate test are shown in figure 8. In this test, temperature measurements were obtained from a resistance thermometer placed at the center of the vessel. All quadrants and the canal were dry during the test.

Both the 20- and 60-foot reference systems were employed. In figure 8 the results of both systems are seen to be in very close agreement. Since the spatial orientation of the system was different, this indicates that the spatial variations in the vessel air temperature were not prohibitively large.

The reference-system and absolute-method results are also seen to be in good agreement; however, the scatter of data is less pronounced in the reference-system results. Accordingly, the reference-system leak rates have smaller limits of error.

Test 2. - The results of the second test are shown in figure 9. Only the 20-foot reference system was employed in this test. The absolute-method temperature measurements were obtained by (1) a system of three thermocouples soldered to the outer surface of the reference system and (2) a resistance thermometer located at the center of the vessel. The two sets of temperatures followed the same cyclical patterns very closely throughout the test, although they differed in indicated magnitudes by about 2°. All the quadrants and the canal were partly filled with water.

Certain data points, as indicated, were not included in the least-squares calculations because their large scatter, in most cases, was believed due to comparatively rapid vessel-air temperature changes, which caused significant spatial temperature variations. It is seen that the reference-system and absolute-method results do not agree as closely as those of the previous test. It is again apparent that there is less scatter of data in the reference-system results. Since the two absolute-method determinations appear to agree well, it may be suspected that the reference system yielded more precise but less accurate results. The most likely source of inaccuracy in the reference-system method, however, is a possible leak in the reference system. Since a leaking system would result in a lower indicated leak rate than the actual, it does not appear that the reference system was malfunctioning in this manner, if at all. Since a third measuring method could not be employed as a standard of comparison, it was not possible to establish one method as being more accurate than the other.

Test 3. - The results of a third test are shown in figure 10. Since the resistance thermometer measurements were known to be erroneous during this test, only two leak-rate determinations were made. Also, during the period from the 13th to the 20th hour, some question existed as to whether the thermocouples were in error. Since this could not be proven, the indications of this period are shown, but their remoteness to the remaining data points was believed sufficient to warrant their omission from least-squares calculations. All the quadrants and the canal were partly filled with water.

During the first 46 hours of the test, the indicated leak rates were as follows:

(1) Absolute method, 0.173±0.032 percent per day

(2) Reference-system method, 0.182±0.017 percent per day

During the last 12 hours, a controlled leak rate was added to the existing vessel leak rate; therefore, this test differed significantly from the previous ones.

During the controlled leak period, the indicated leak rates were the following:

(1) Absolute method, 0.424±0.055 percent per day

(2) Reference-system method, 0.390±0.040 percent per day

The controlled leak rate introduced was measured to be 0.226±0.002 percent per day (1115 cu ft/day). Subtracting this amount from the indicated rates of this period results in the following leak rates:

(1) Absolute method, 0.198±0.055 percent per day

(2) Reference-system method, 0.164±0.040 percent per day

Comparing these rates with those indicated in the first 46 hours shows that all of them overlap. Thus, both the general agreement and the accuracy of both measuring methods are indicated experimentally.

During the controlled leak period, indications are that the vessel air temperature remained virtually constant, and thus there is very little scatter of data. Since the confidence interval of the leak rate depends on both the scatter of data and the test duration, however, the confidence intervals of the controlled leak period are comparable to those of the first 46 hours.

Temperature Measurements

The percent loss results shown in figures 8 to 10 indicate that generally the only time undue scatter occurred was during comparatively rapid temperature changes. It also appears that any temperature changes were accompanied by an increase in the scatter of results. Since it was shown in the thermal-time-lag analysis that the reference system is virtually free from thermal-time-lag inaccuracies, such scatter may be attributed to the concurrence of

(1) Incomplete sampling of the vessel atmosphere

(2) Spatial temperature variation of the vessel air

The foregoing conclusions also apply to the absolute-method results.

From figures 8 to 10, it is obvious that the scatter of results was never so great as to make the trend of data unrecognizable or unmeaningful, which indicates to some extent the accuracy of the average temperature and water vapor pressure measurements. It is estimated that the system of thermocouples measured the average air temperature to within $\pm 0.4^{\circ}$ F, whereas the reference system measured to an estimated $\pm 0.2^{\circ}$ F. The precision of the individual thermocouple measurements is actually considerably greater, but unavoidable sampling errors broaden the limits of error in the average temperature measurement.

Although the accuracy of both methods was experimentally verified by means of the known leak-rate method, the scatter of future test results could probably be reduced by increasing the number of temperature and dewpoint sensors employed.

Various Testing Experiences

In the first test all leak searches were conducted outside the vessel. In subsequent tests, many more leaks were found by entering the vessel through the air locks while the vessel was at the testing pressure and listening for leakage. When as many systems as possible were shut down, the noise level within the vessel was low enough to allow even minute leaks to be heard. The largest leaks found were through valves and around electrical cable penetrations. In the latter case about half of the leaks were between the cable sheath and the potting in the penetration seal. In the other half leakage occurred along the inside of the cable and was due to faulty end potting on cut cable sheaths. A quick setting rubber cement was used for repair. All these leaks were easily fixed, since the air pressure forced the cement into the leak with a self-caulking action. Door seals were observed to leak only slightly. Only two faulty pipe penetrations were found.

Experiences have shown that the time required to prepare the reference system for use in an initial leak-rate test is considerable. The principal difficulty was keeping manometer fittings and connections leak tight. To ensure the tightness of the reference system, it was necessary to conduct a 48-hour pressurization test at 4 pounds per square inch gage. Actually the pressurization test might have been completed in a shorter time by conducting the test at a higher overpressure. In the second and third tests the overall time expenditure was considerably reduced, since the only likely source of leakage was the junction of the reference-system and valve-system tubing because the reference system was in storage between tests.

A very desirable feature of the reference-system method was its ability to yield raw data (pressure differentials), which could be interpreted directly in terms of a rough leak rate. Thus, it was possible to determine conveniently the change in leak rate as additional leaks were found and sealed during the leak-searching period. Hence, it was possible to avoid beginning a 48-hour test until the ΔP changes indicated a leak rate significantly lower than the allowable.

The outstanding feature of the absolute method was its simplicity. The problems associated with the preparation and installation of a few thermocouples were far smaller than those associated with the preparation of the reference system.

SUMMARY OF RESULTS

Leak-rate testing of the Plum Brook Reactor (PBR) containment vessel by the absolute-temperature-pressure method and the reference-system method revealed the following:

1. Thermal-time-lag effects in the reference-system method may be made insignificant by making the reference system of sufficiently small-diameter tubing (approx. 1/2 in.). Consequently, the accuracy with which such a reference system senses the average vessel air temperature is likely to be limited by sampling errors.

2. The thermal-time-lag effects in the reference systems employed in these tests were negligible. Consequently, both systems were temperature compensating.

3. In all three tests the leak-rate determinations of both methods were in substantial agreement.

4. In all cases the reference-system results showed less scatter than the absolute-method results; that is, the reference system measured the leak rate with slightly greater precision.

5. For PBR conditions, the absolute method, while yielding results with more scatter than those of the reference-system method, offers the advantage of greater overall simplicity. However, the reference system proved to be an accurate and satisfactory method of measurement.

6. The accuracy of the leak-rate results may be conveniently illustrated experimentally by superimposing a known leak rate upon the vessel leak rate during part of the test period.

7. The pressure differential data obtained from the reference system permitted the simple and convenient approximation of the leak rate, which was valuable in reducing the overall testing time.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, April 18, 1963

APPENDIX A

SYMBOLS

a	radius of cylinder
f	frequency of temperature variation
P	pressure
ΔP	difference in pressure between containment vessel and reference system
R	gas constant
r	radial distance to any point within cylinder
T,t	temperature
V	volume
W	weight of air
κ	thermal diffusivity
τ	time
ω	circular frequency of temperature variation, $2\pi f$
ω'	$\sqrt{\omega/\kappa}$

Subscripts:

act	actual value
h	water-vapor pressure
ind	indicated or measured value
r	reference-system properties
s	indications of any system of temperature sensors
v	containment-vessel properties
0	time at which pressurization is completed and reference system is isolated from containment vessel
1	time of first measurements
2	time of any later measurements

APPENDIX B

EFFECTS OF TEMPERATURE AND PRESSURE MEASUREMENT ERRORS

Although the apparent principal difference between the absolute and reference-system methods is the means of temperature measurement, the comparative scatter of the percent loss results is partly a result of the nonindependence of the "temperature" and pressure measurements in the reference-system method. To illustrate this, equations (4) and (13) are rearranged as follows:

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{T_{s,1}}{P_{v,1}} \frac{P_{v,2}}{T_{s,2}} \tag{B1}$$

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,1} + \Delta P_1}{P_{v,1}} \frac{P_{v,2}}{P_{v,2} + \Delta P_2} \tag{B2}$$

It is seen that any errors present in the measurements at τ_1 become a source of fixed error in the results of both methods. Since a leak rate is being measured, a fixed error is of little consequence. For the measurements by the reference-system method at τ_2, an error in $P_{v,2}$ will result in the same error being introduced into the "temperature" measurement $(P_{v,2} + \Delta P_2)$. The ratio $P_{v,2}/(P_{v,2} + \Delta P_2)$, however, will not be changed significantly. Using values typical of Plum Brook Reactor tests, a 1-percent error in $P_{v,2}$ will result in an error of only 0.01 percent in the ratio $P_{v,2}/(P_{v,2} + \Delta P_2)$. In the reference-system method, then, the temperature and pressure measurements are, in a sense, coupled. This results in the virtual cancellation of pressure measurement errors.

In the absolute method, an error in $P_{v,2}$ is quite independent of the measurement of $T_{v,2}$. Thus, even if the temperature measurements were extremely precise and accurate, any pressure measurement errors would produce scatter in the percent loss results. In this case a 1-percent error in $P_{v,2}$ will also result in a 1-percent error in the ratio $P_{v,2}/T_{v,2}$.

Thus, the reference-system method is relatively insensitive to errors in the measurement of the absolute vessel pressure. An excellent illustration of this may be seen in certain points (tailed symbols) of test 2 in figure 9. From figure 11, which is a plot of temperature, barometric-pressure, and water-vapor-pressure variations during test 2, it appears that the barometric pressure measurements for these points are in error (probably human errors). Yet, since the same error is introduced into both the "temperature" and pressure measurements of the reference-system method, no noticeable error is evident in the percent loss results of figure 9. By the absolute method, however, the percent loss results for three of the four points are off scale.

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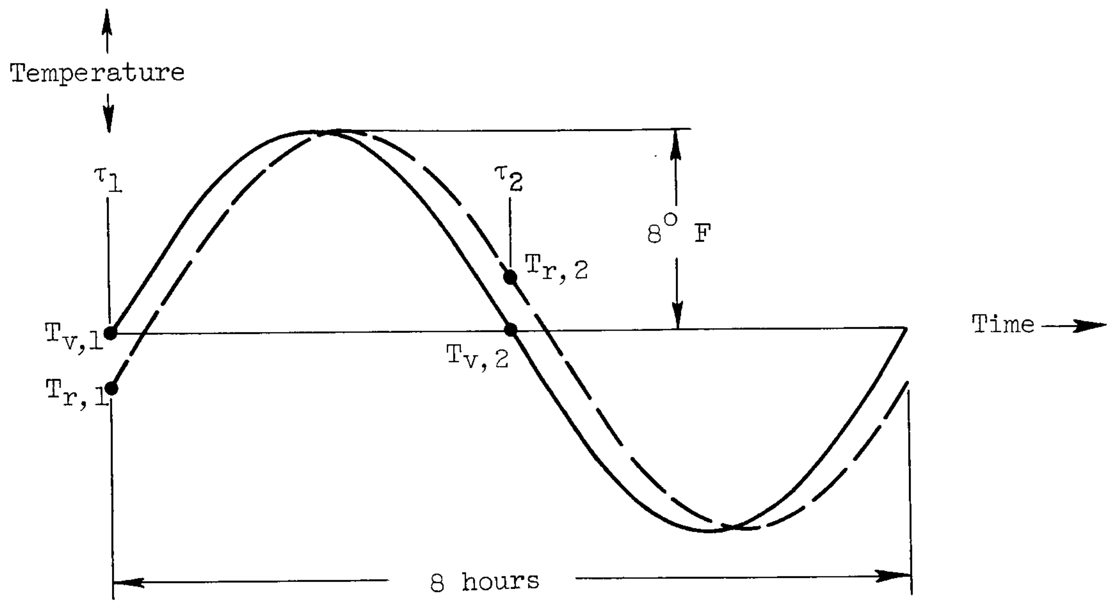
TABLE I. - EFFECTS OF THERMAL-TIME-LAG ERRORS ON FRACTIONAL WEIGHT LOSS

INDICATIONS OF THREE REFERENCE SYSTEMS



Reference-system diameter, in.	Actual reference-system temperature, T_r, $^\circ$F, Time, τ: τ_1	τ_2	Indicated weight loss, $\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} \times 100$, percent	Actual weight loss, $\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{act} \times 100$, percent ($T_{v,1} = T_{r,1}$, $T_{v,2} = T_{r,2}$)	Maximum percent error, $\frac{act - ind}{act}$
2	529.99	530.01	0.298	0.294	1.4
12	529.30	530.70	.557	.294	89
24	527.80	532.20	1.118	.294	280

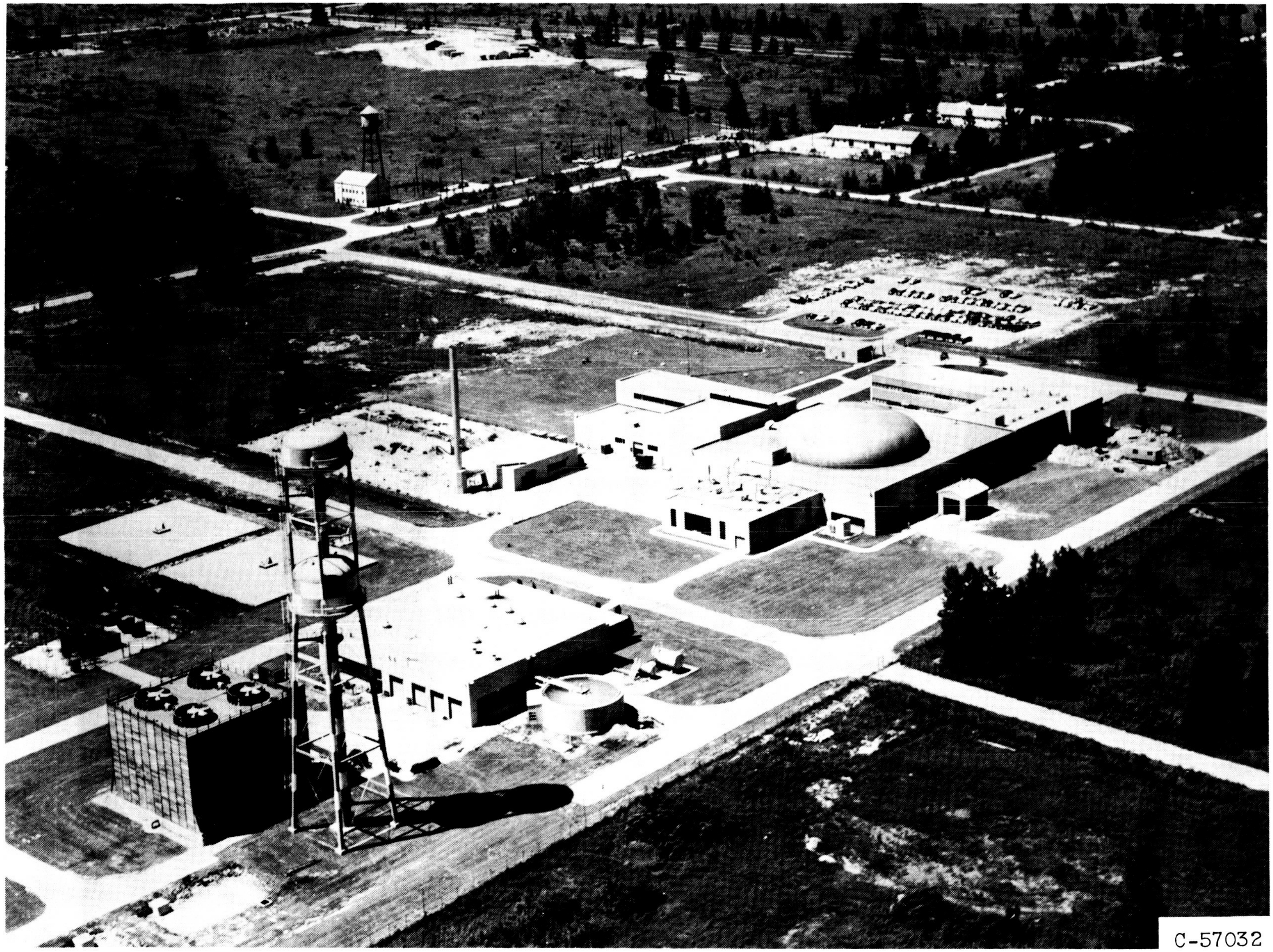


Figure 1. - NASA Plum Brook Reactor.

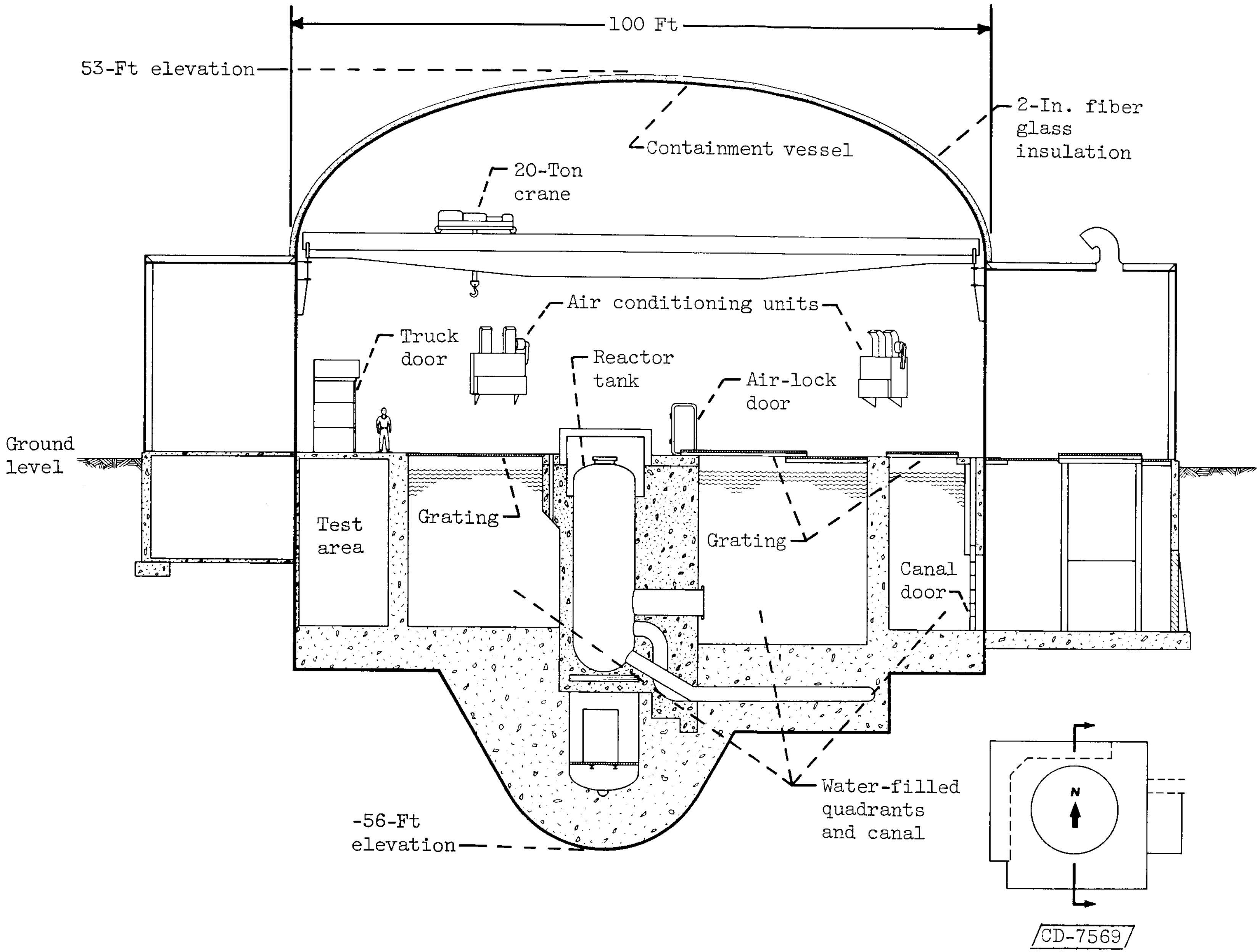


Figure 2. - Vertical section of reactor building.

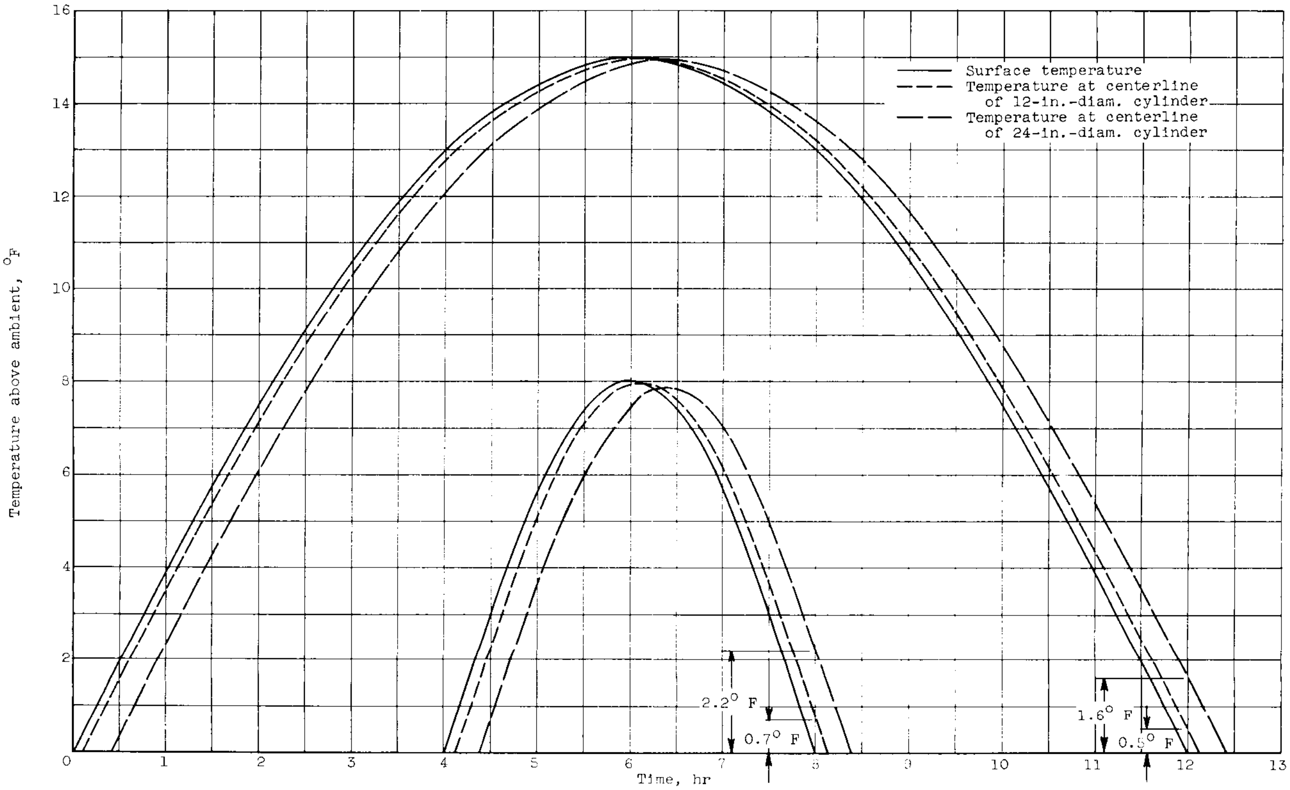


Figure 3. - Steady-state temperature variation at centerline of infinite cylinder for sinusoidally varying surface temperature.

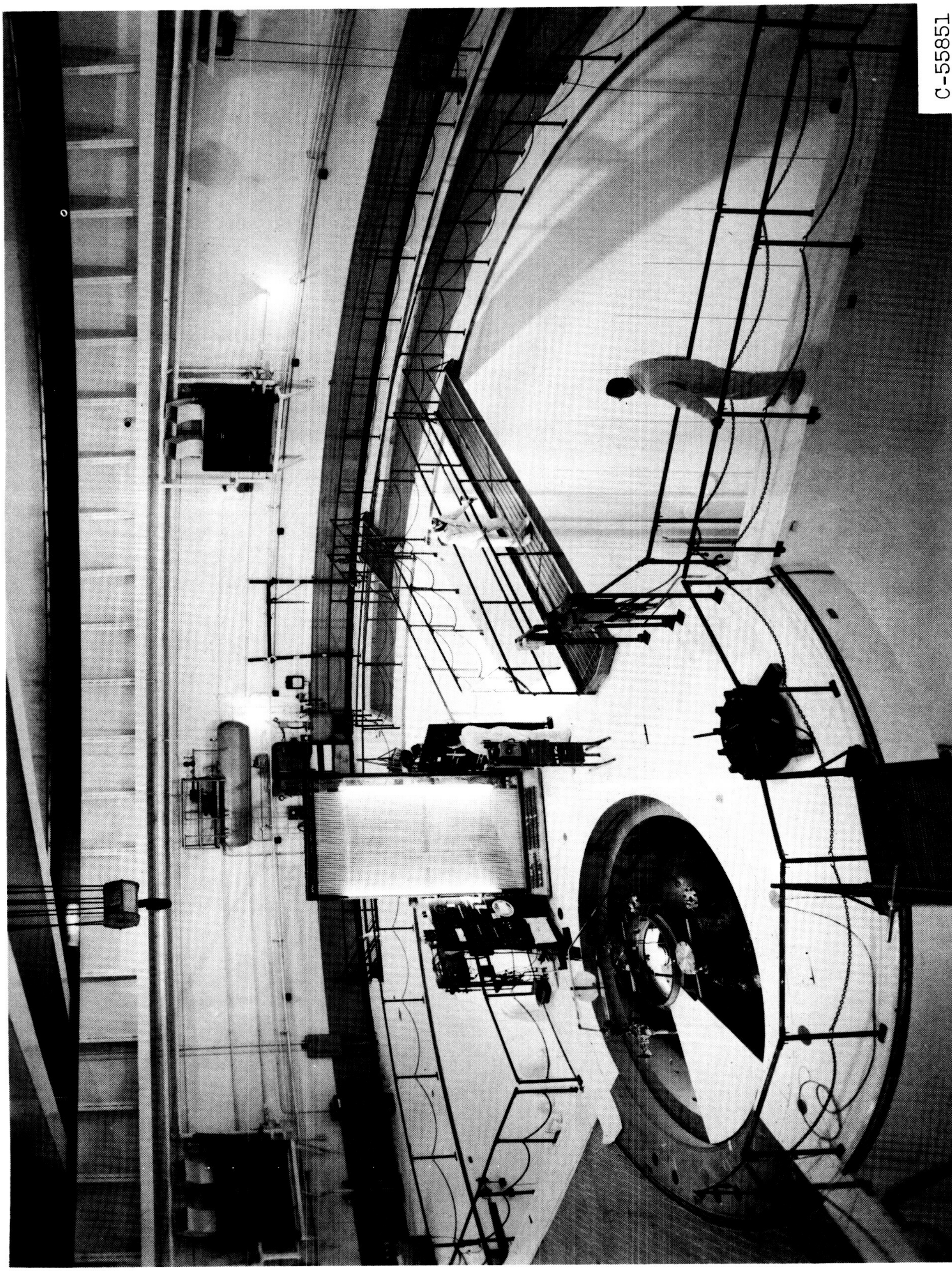


Figure 4. - Containment-vessel interior.

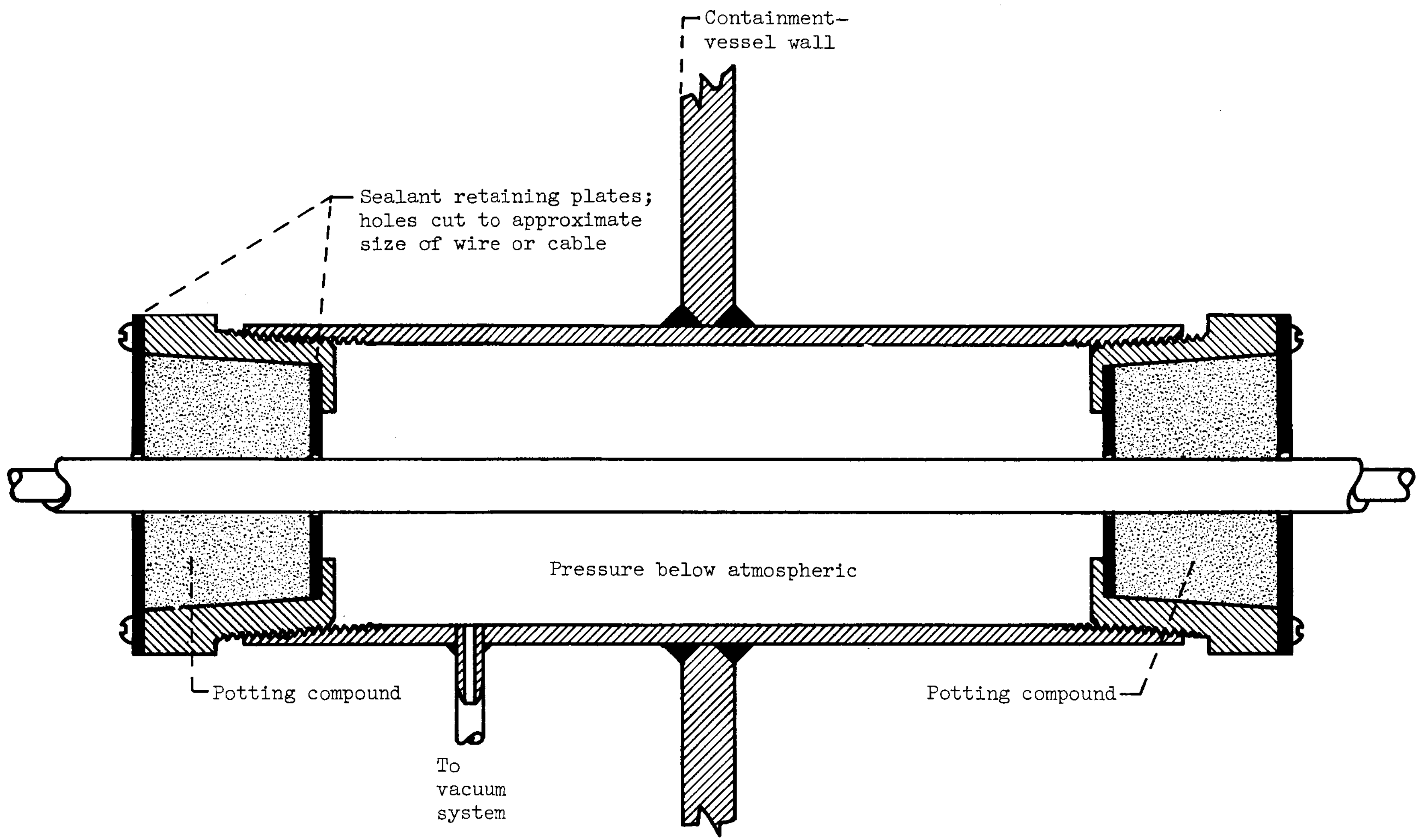


Figure 5. - Typical wire or cable penetration.

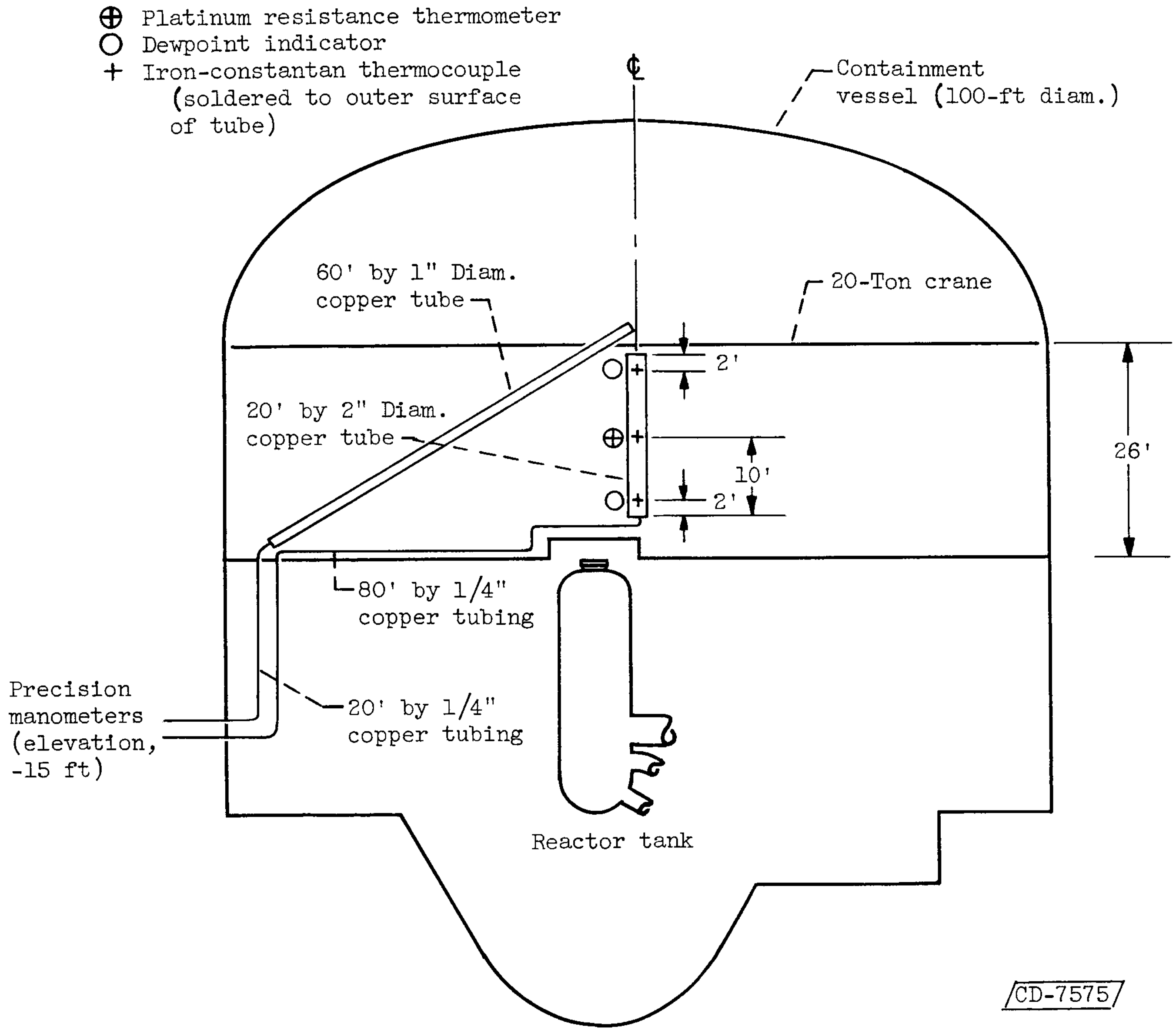


Figure 6. - Location of instruments.

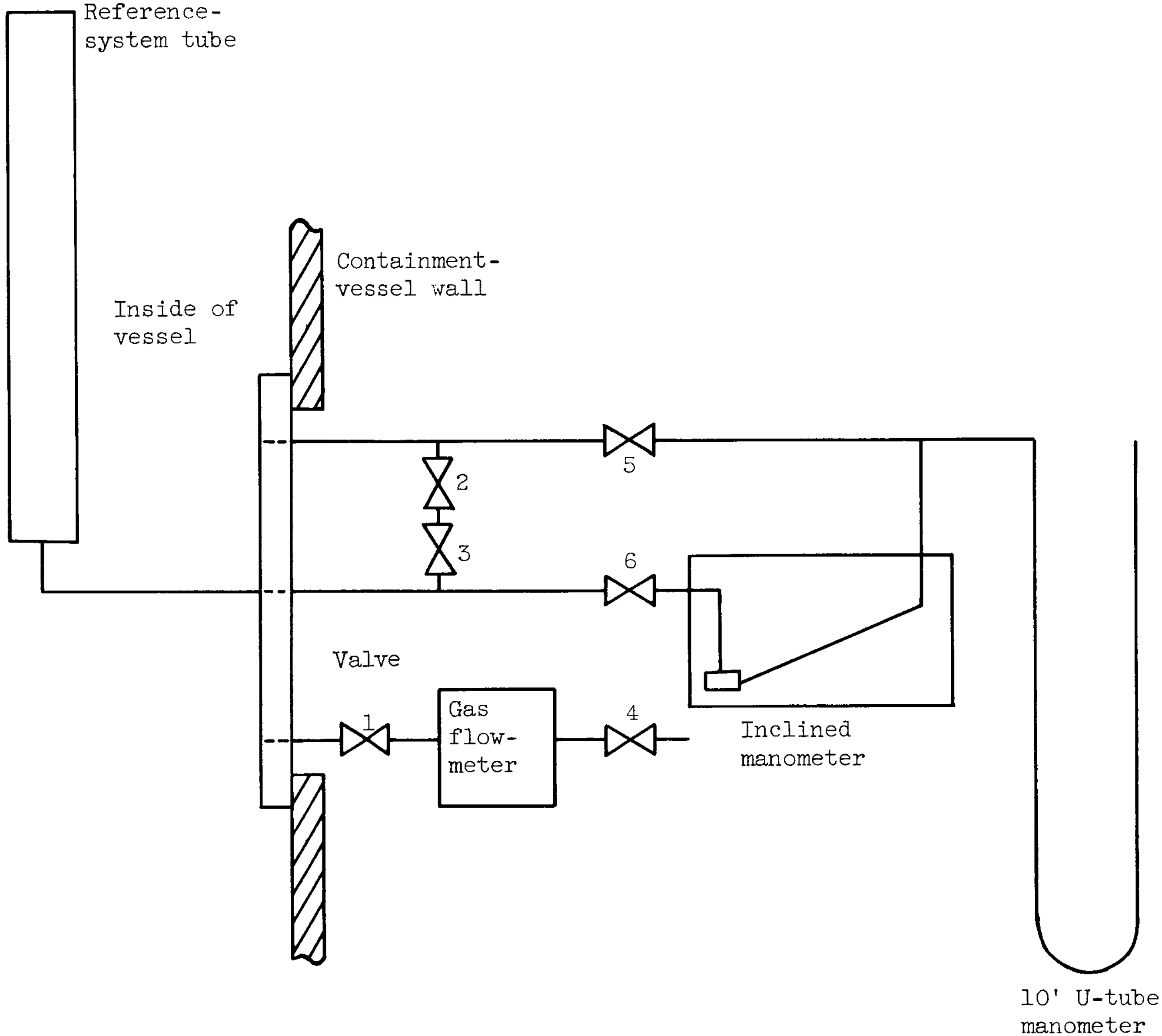
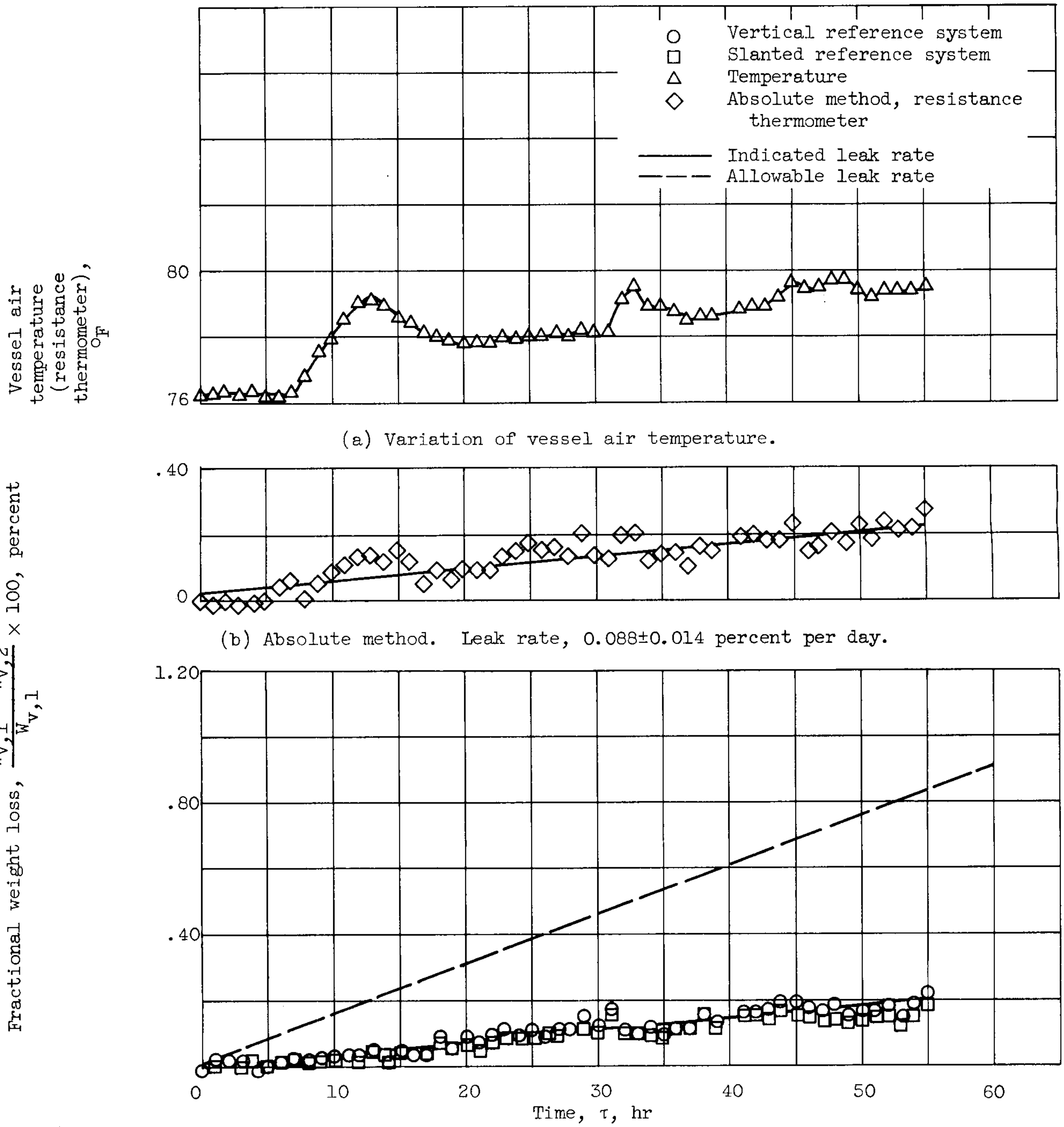
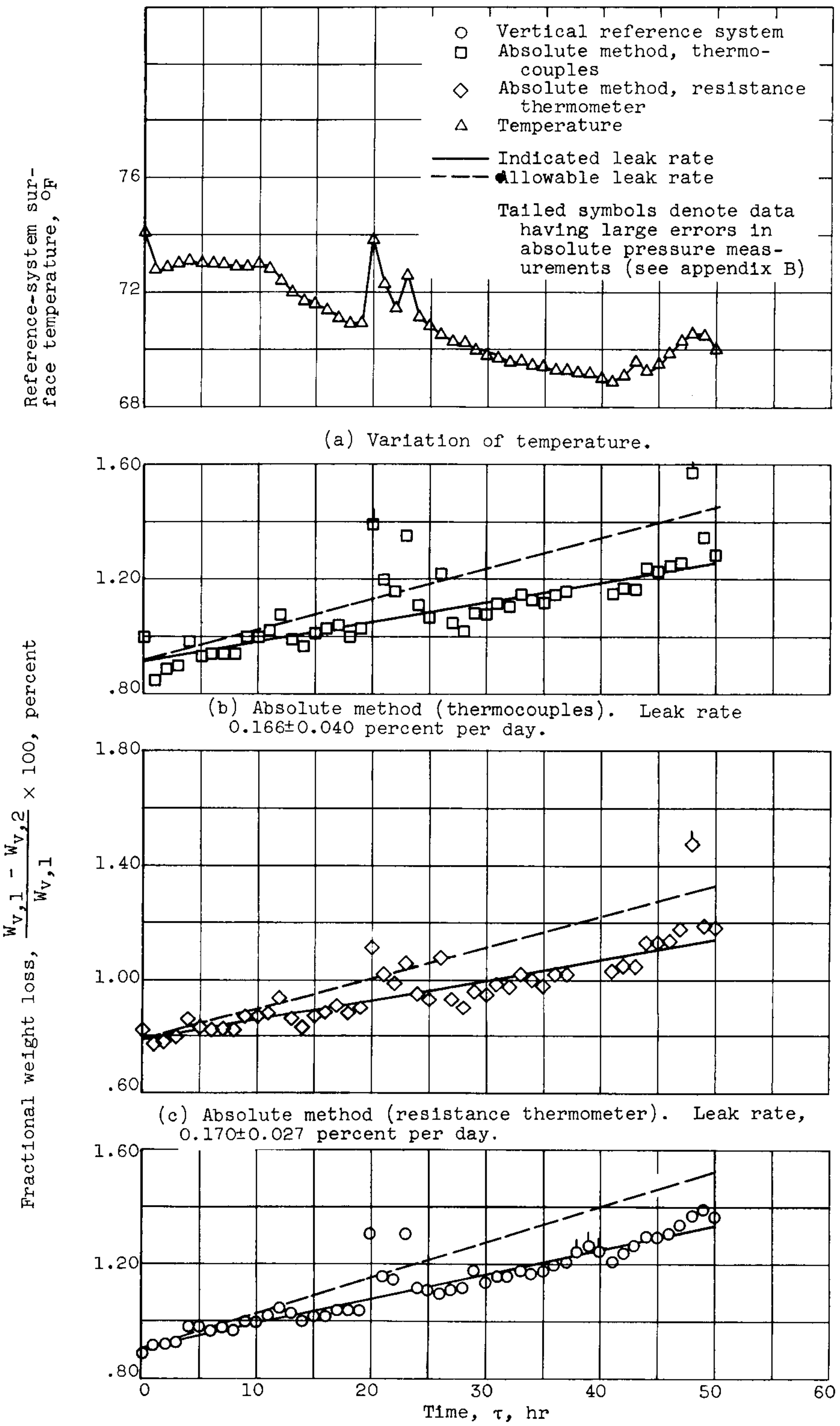


Figure 7. - Schematic of reference system.



(c) Reference-system method. Leak rate for vertical system, 0.086±0.008 percent per day.

Figure 8. - Leak-rate test 1. Fractional weight loss of vessel air and vessel air temperature as functions of time.



(a) Variation of temperature.

(b) Absolute method (thermocouples). Leak rate 0.166±0.040 percent per day.

(c) Absolute method (resistance thermometer). Leak rate, 0.170±0.027 percent per day.

(d) Reference-system method. Leak rate, 0.207±0.020 percent per day.

Figure 9. - Leak-rate test 2. Fractional weight loss of vessel air and vessel air temperature as functions of time.

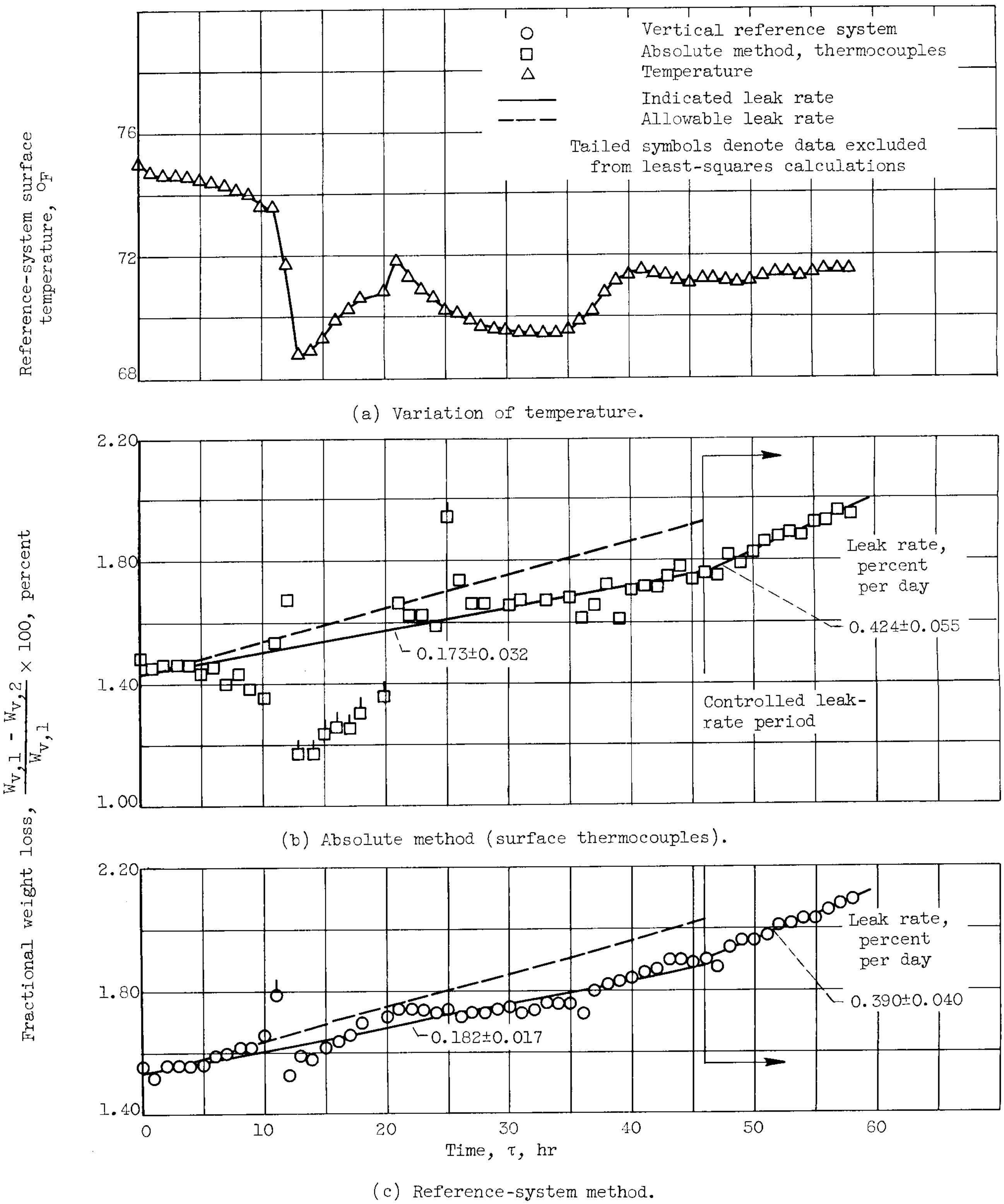


Figure 10. - Leak-rate 3. Fractional weight loss of vessel air and vessel air temperature as functions of time.

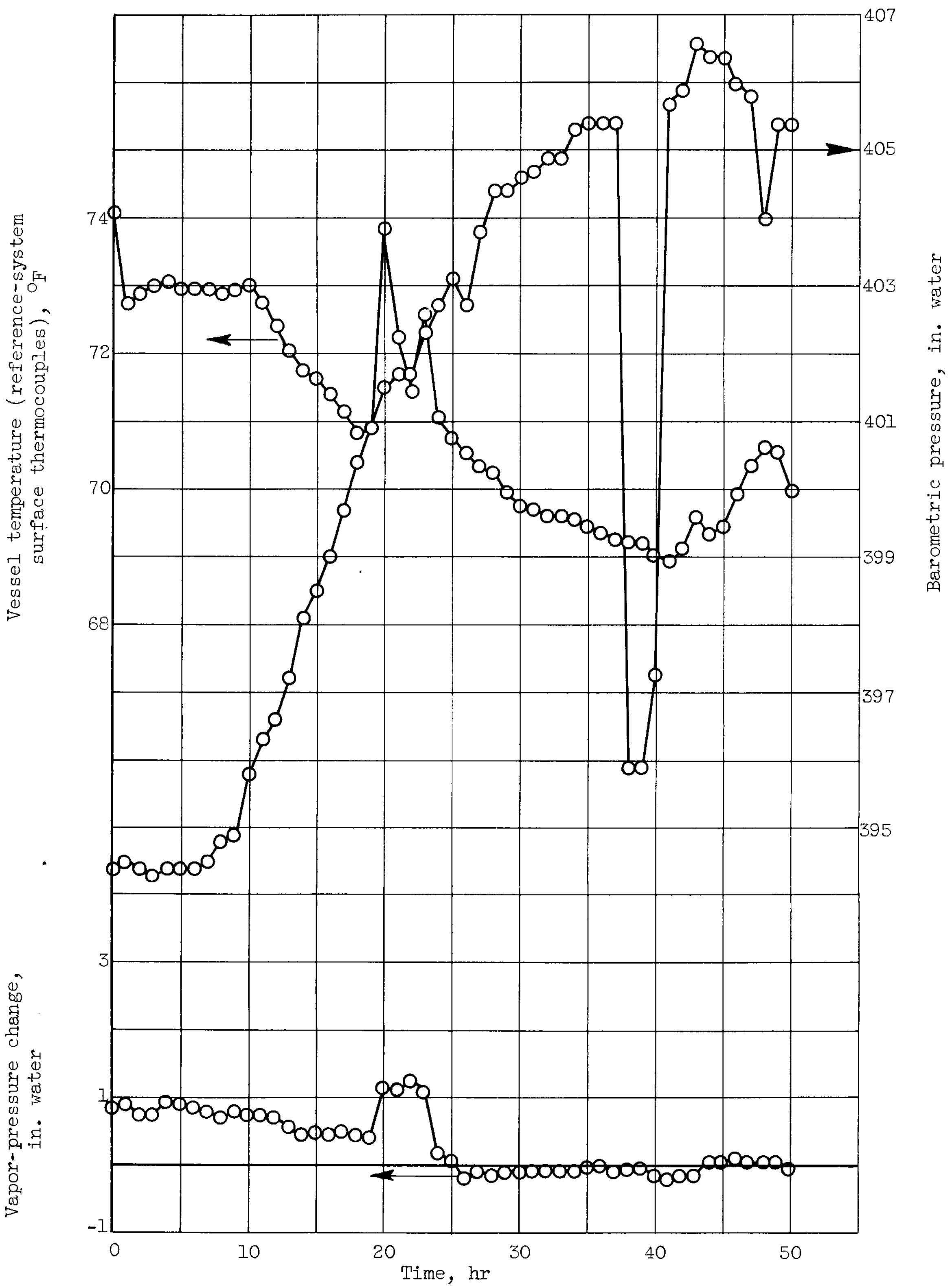


Figure 11. - Pressure and temperature variations during leak-rate test 2.